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Predict Frequency Accuracy For MC12060 And MC12061 Crystal Oscillator Circuits

Crystal oscillators are used when it is necessary to generate a precise and highly stable signal. Such circuits typically provide this stable signal at a frequency close to the resonant frequency (either parallel or series) of their crystal. However, circuit components and other factors external to the crystal influence the crystal's natural resonance to some degree, an effect often referred to as "pulling" or "warping." A discussion of the variation in crystal frequency as a function of differing ICs*, temperature, and dc supply voltage is presented in this bulletin to aid the designer in predicting the amount of frequency pull in his particular design.

Crystal Characteristics

As shown by the equivalent circuit of Figure 1, crystals behave as open circuits to dc. For ac signals below a crystal's series resonant frequency, the crystal exhibits a capacitive reactance. As frequency increases, the series resonance of C_S and L_S is reached. The crystal then appears as a low value resistor, R_S, shunted by a small capacitance, C_O. At frequencies above series resonance, the C_S, L_S combination appears as an inductive reactance. As frequency increases even higher, the inductive reactance grows eventually equalling the capacitive reactance of C_O. This is the high impedance, parallel resonant frequency for the crystal. Although the separation in frequency between series and parallel resonance varies for different crystals, series resonance will typically occur several hundred Hertz to a few kilohertz below parallel resonance.

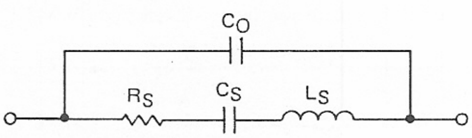


FIGURE 1 — Crystal Equivalent Circuit

Crystals used with MC12060/61 devices must meet the requirements specified in their data sheet. Since these devices oscillate at the frequency that provides the lowest impedance (series resonance) between pins 5 and 6, a crystal must not exhibit a spurious response resulting in impedance values near or less than the desired series resonance impedance. In the evaluations discussed here, standard commercial crystals with ±0.0025% calibration tolerance, fundamental mode, were used with the MC12060/61 devices. Measured series resonance frequencies for the crystals used, along with equivalent series inductance (L_S) and resistance (R_S) values are presented in Table I.

*Specifically, the Motorola MC12060/12560 and MC12061/12561 integrated circuits which are designed for use with an external fundamental series resonant crystal. Specified operating frequency range is 100 kHz to 2 MHz for the 12060/12560 and 2 MHz to 20 MHz for the 12061/12561. Complementary sine wave, com-

TABLE I
Crystal Parameters

Series Resonant Frequency (MHz)	Equiv. Series Resistance R_S (Ohms)	Equiv. Series Inductance L_S (mH)
2.500025	38.0	274.0
8.079977	8.4	17.6
13.411100	6.9	7.0
18.749563	12.5	2.9
19.999528	9.2	–
(kHz)		
100.002	497	–
200.012	509	–
500.031	995	9857
999.985	380	2629
2000.032	96	526

plementary ECL, and single ended TTL outputs are available. Complete technical specifications for these ICs can be found on the device data sheet. Additional applications information is available in Motorola application note AN-756 and engineering bulletin EB-60.

MC12060/61 Performance

The circuit elements in an oscillator environment have an effect on the fundamental resonant frequency of a crystal. To measure the influence of the MC12060/61 devices, tests were made using the circuit of Figure 2. Frequency measurements were taken at the sine wave output (pin 2 or pin 3), the 680 ohm resistor making it possible to drive a 50 ohm load. Laboratory quantities of the ICs were tested, consequently some variation in results could be expected if a production run cross section were evaluated.

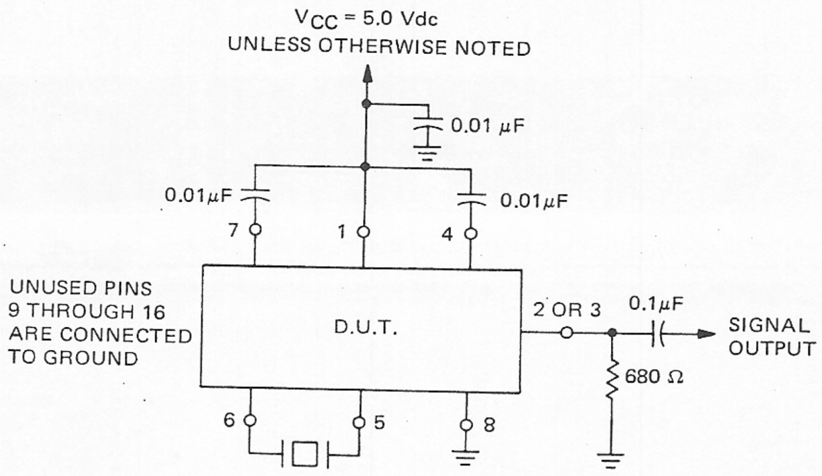


FIGURE 2 — MC12060/61, MC12560/61
Evaluation Circuit

The measured pull of the MC12060/61 devices on a crystal's series resonant frequency is shown in Table II for room temperature operation. Resonant frequency is always reduced, the effect becoming more pronounced with increasing operating frequency. Where minimum pull is required, the MC12061 rather than the MC12060 should be considered for use at or slightly below 2.0 MHz. Table III shows the variation in pull on the same crystal resulting from the use of different MC12060 and MC12061 devices.

Figure 3 gives the frequency shift caused by the MC12560/61 devices operating over their temperature range of −55°C to +125°C. Similar results can be expected for the MC12060/61 devices over their specified range of 0°C to +75°C. Data was taken with the crystals at a constant temperature of approximately +25°C to isolate the effect of temperature on the ICs. Since the curves are normalized, one must add the appropriate room temperature value (see Table II) to obtain the net frequency pull at a specific temperature. For example, the MC12561 device operating with the nominal 8.08 MHz crystal would exhibit a net pull of approximately −40 − 11 = −51 PPM at +125°C. The curves show a small temperature dependence at lower frequencies that increases significantly above midband. Although not plotted, over the −55°C to +85°C range MC12560 at 2 MHz and MC12561 at 18.75 MHz changed from +155 to −275 and from +7 to −45 PPM respectively, referenced to +25°C.

TABLE II
Crystal Frequency Pull In Percent For MC12060/61 IC's

DEVICE	MC12060					MC12061				
NOMINAL CRYSTAL FREQUENCY (MHz)	0.100	0.200	0.500	1.00	2.00	2.50	8.08	13.41	18.75	20.0
CRYSTAL PULL IN PERCENT	*	−0.0005	−0.0012	−0.0040	−0.03	−0.0002	−0.004	−0.01	−0.03	−0.05

*LESS THAN 1 Hz, MEASUREMENT LIMITED BY RESOLUTION OF TEST EQUIPMENT.

TABLE III
Measured Frequency Deviation From Device to Device

NOMINAL FREQUENCY (MHz)	FREQUENCY DEVIATION (Hz)	(PPM)
MC12060		
0.100	*	*
0.200	*	*
0.500	2	4.0
1.000	10	10.0
2.000	165	82.5
MC12061		
2.50	2	0.8
8.08	110	13.6
13.41	485	36.2
18.75	1755	93.6

*Less than 1 Hz, Measurement limited by resolution of test equipment.

pacitor and its effect on increasing frequency. Therefore, if only a small increase in frequency is required, the trim capacitor value may become unreasonably large. To assure a suitable value for the capacitor, it may be necessary to specify the crystal frequency lower than the actual desired operating frequency. The pulling effect of the ICs will normally be much less than that of the trim capacitor and therefore the crystal can simply be specified such that the series combination of crystal and trim capacitor is in series resonance at the desired operating frequency. If it is also desired to account for the effects of the ICs, this may be approximated by considering the MC12060 to add 266 μH and the MC12061 1.6 μH in series with the crystal.

As a typical example, assume that the MC12061 is to be used with a nominal 8 MHz crystal having an equivalent series inductance L_S = 17.6 mH. Figure 5 shows the equivalent circuit. With no C_{TRIM} added, the IC will lower the crystal's resonant frequency by approximately $\sqrt{(17.6 + 0.0016)/17.6}$ or 0.0045%. Use of a 10 pF trim capacitor would place a net impedance in series with the crystal of $j\omega L_{IC} - j\ 1/\omega C_{TRIM} = -j\ 1.909 \times 10^3$. This corresponds to an equivalent capacitance in series with the crystal of $C_{EQUIV} = \dfrac{1}{2\pi \times 8 \times 10^6 \times 1.909 \times 10^3} =$

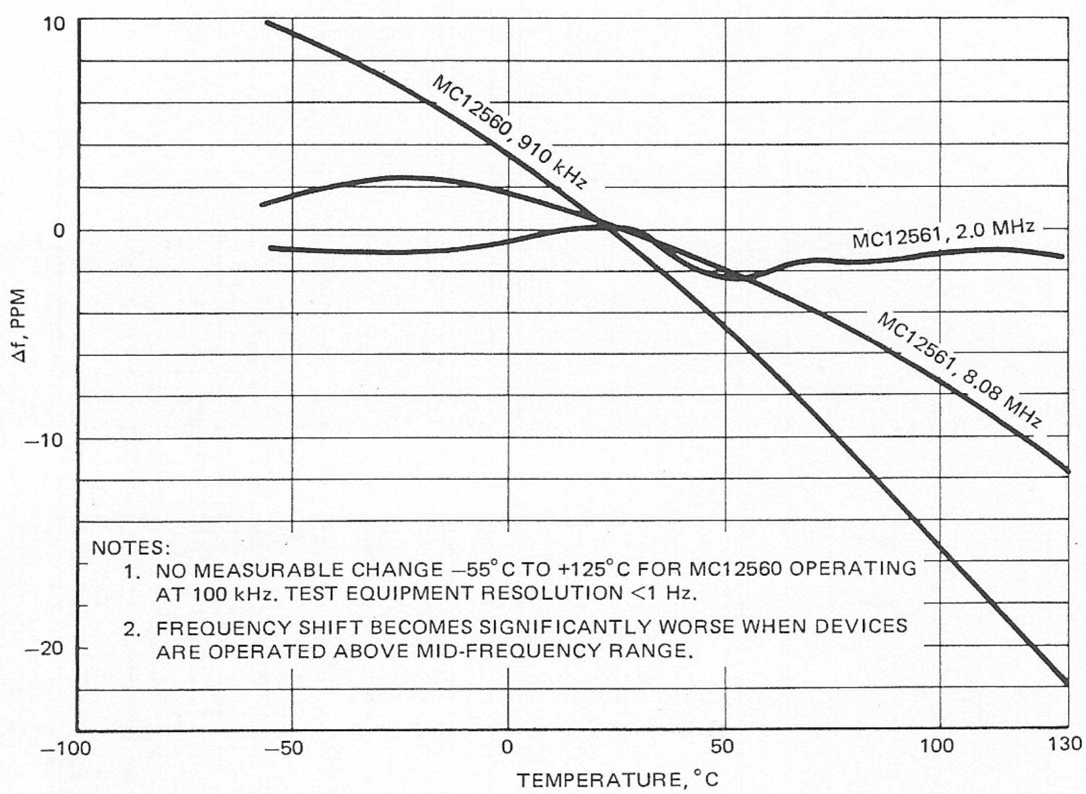


FIGURE 3 — Frequency Shift VS Temp. with Crystal Located Outside Temp. Chamber

Figure 4 provides plots of frequency pull as a function of change in dc supply for the MC12060/61 devices.

Design Example

The ICs are designed to pull the crystal's natural series resonant frequency lower. If desired, this permits a trim capacitor to be inserted in series with the crystal to set the oscillator "on frequency". Since this trim capacitor is approximately in series with C_S of the crystal, there is an inverse relationship between the value of the trim ca-

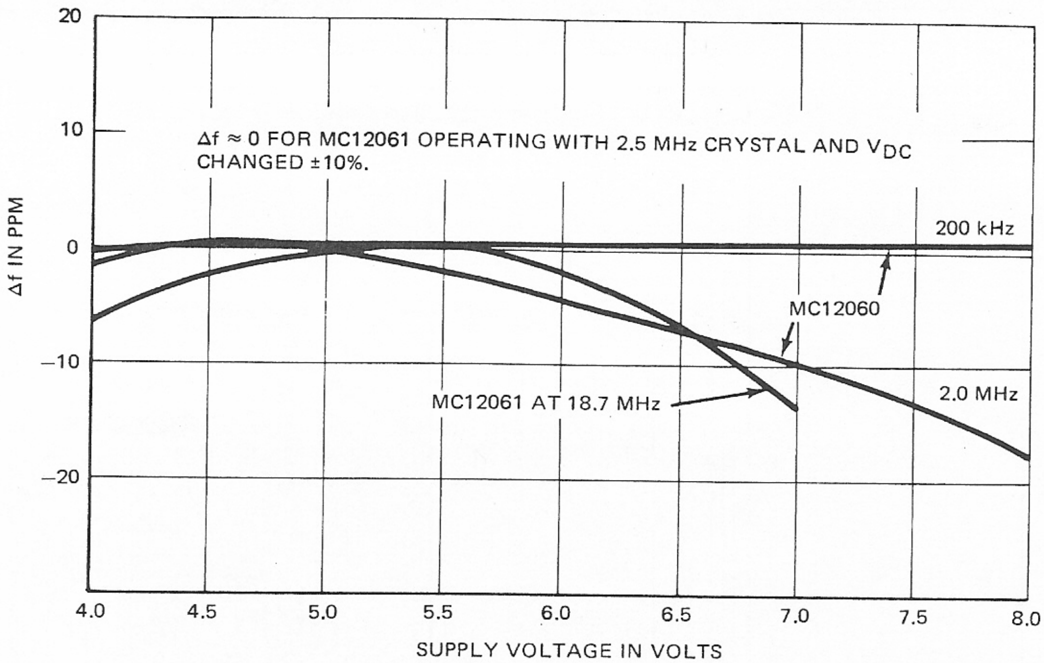
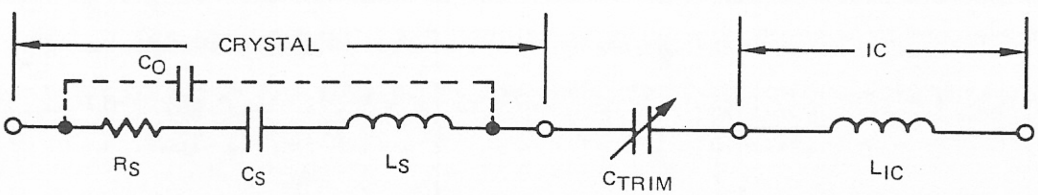


FIGURE 4 — MC12060/61 Frequency Shift Versus DC Supply Voltage Value



C_O is assumed negligible at the frequency of series resonance for the crystal.

FIGURE 5 — Crystal/IC Oscillator Equivalent Circuit

10.42 pF. The crystal should be specified so that the crystal reactance and that of C_{EQUIV} are in series resonance at the operating frequency (8.000 MHz). In effect, this requires a crystal with a series resonance slightly below 8.000 MHz so that at precisely 8.000 MHz it presents a +j impedance which equals the −j impedance supplied by C_{TRIM} in series with L_{IC}, i.e., C_{EQUIV}.

If the crystal is not resonant below 8 MHz as suggested, but rather at exactly 8 MHz, C_{TRIM} must then be chosen to resonate with an L_{IC} inductance of 1.6 μH requiring an undesirably large value of 247 pF. The C_{TRIM} value can approach infinity if the crystal calibration tolerance allows the crystal to be series resonant on the high side of 8 MHz.

A similar procedure can be followed for the MC12060 device. In this case the approximation L_{IC} = 266 μH is used. The calculated frequency pull for the nominal 500 kHz, 1 MHz and 2 MHz crystals described in Table I is then −0.0013, −0.0051 and −0.0253 percent respectively. This agrees closely with the measured values of −0.0012, −0.0040, and −0.03 percent given in Table II.

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